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SMOKE EMISSIONS FROM WILDLAND FIRES

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Biomass burning is a major source of emissions to the atmosphere. Some of these emissions may change global climate. This paper uses combustion efficiency as an independent variable for predicting emission factors for, among others, carbon monoxide, carbon dioxide, methane, and particulate matter. Other gases are correlated with the release of carbon monoxide. The release of nitrogen and sulfur-based compounds occurs in relation to their content in the biomass. The Sundance Fire is used to model the emissions from major fires that have occurred in the United States. Approximately 1 Tg of biomass was consumed by this fire, which released 0.019, 0.151, 1.545, and 0.007 Tg of particulate matter, carbon monoxide, carbon dioxide, and oxides of nitrogen, respectively. Other fires have released over 50 times this amount. Global emissions of various products of combustion are dependent on the combustion efficiency of the fires.

INTRODUCTION

Biomass burning is a major contributor of "greenhouse" gases and particulate matter to the atmosphere. The net effect on global climate is not well quantified, and there is a need for better source information regarding the total biomass consumed globally and the quantity and time of release of the important emissions. Radke (1989) estimates that, on a global scale, 10 Pg/y (Pg = Petagram, 10^{15} g) of biomass are consumed. This includes all forms of biomass consumption. Seiler and Crutzen (1980) estimated global biomass burning to contribute 2-3.3 Pg of carbon in the form of carbon dioxide to the atmosphere each year. Crutzen et al. (1985) estimated carbon monoxide emissions of 0.8 Pg/y from biomass burning. Hegg et al. (1989) estimated the production of several trace gases based on the ratio of trace gas to CO emission ratios. Estimates of biomass consumption based on chemical mass balance considerations may be lower than previously estimated because of new information on the efficiency of the combustion processes that produce CO_2 emissions. In this paper, we discuss factors that lead to the production of incompletely oxidized combustion products and the significance of these on the global production of emissions. A large wildfire, the Sundance Fire of 1967, is modeled and used to estimate emissions from other historically important, large wildfires. Models describing the rate of emission per unit mass of fuel consumed are presented as a function of combustion efficiency. Combustion efficiency is defined as the percentage of carbon released during

combustion of biomass fuels in the chemical form of carbon dioxide.

In the United States 1988 was one of the most extreme "fire years" in recent history. Wildfires burned 2 Mha of land, including 300 000 ha in Yellowstone National Park. If we consider an average fuel consumption of 45 Mg/ha, the total fuel consumed by wildfires in the United States in 1988 was 90 Tg (Tg = Teragram, 10^{12} g). In addition, Chi et al. (1979) estimated that prescribed fires burn an average of 36.6 Tg of biomass per year. The total wildland biomass fuel consumed by planned fires and wildfires in the United States represents less than 2% of the estimated global biomass consumption.

Historically, smoke from biomass fires has been a major societal problem. Only since about 1970 has information been developed describing the content of smoke. Interpreting the effects of smoke on health and radiation transfer through the atmosphere is continuing. Much of the research has focused on smoke production for prescribed fires, basically using three techniques:

1. Ground level measurements with instruments on towers or suspended in smoke from near full-scale prescribed fires (Ward and Hardy 1984; Ward et al. 1989a).

2. Airborne measurements by flying instrumented aircraft through the plumes of prescribed fires of different fuel loadings (Radke et al. 1990).

3. Modeled fuels burned in controlled environment combustion laboratory facilities (Ward 1989).

The few direct measurements of smoke emissions from wildfires were made in conjunction with an examination of the assumptions on which the nuclear winter hypothesis was based (Turco et al. 1984 1990; Crutzen and Birks 1982; Radke et al. 1988; Hegg et al. 1989). This paper summarizes existing data and applies the information to a well-documented wildfire. The model for the wildfire is used to estimate emissions for other historical fires and to provide new concepts regarding global emissions from biomass fires.

Large biomass fires, historically, have been a major source of smoke emissions to the atmosphere. Plummer (1912) describes in detail smoke phenomena in emphasizing that forest fires are tremendously damaging economically. We quote here from the observations of Plummer (1912):

"A thrifty forest purifies the air we breathe, and it is an irony of nature that when it goes up in smoke it causes a pollution of the atmosphere. The mischief thus caused is by no means trivial, since a heavy pall of smoke interrupts business, interferes with navigation, and, turning [day] into [night], compels the use of artificial light. Such conditions have [occurred] over an expanse of many thousands of miles, and the actual loss must be very great. In the vicinity of a great fire the atmosphere sometimes carries ashes and burning brands to a distance of several miles....Forest fires are the most frequent cause of widespread pollution of the atmosphere, and the volume of the pollution is exceeded only in the case of violent volcanic eruptions....A large forest fire has an appreciable effect upon the surrounding atmosphere, causing a movement of the air toward the fire. This effect is quite local, and is overbalanced if there is a strong wind blowing, which will drive the fire before it....During the great forest and city fire at Fernie, British Columbia, August 1-8, 1908, which was accompanied by a high wind, flaming trees, timbers, lumber, and sections of buildings were carried. This fire burned a strip 3 miles wide for a distance of about 20 miles. During the great Idaho fire of August 20-22, 1910, the same phenomena were observed....The tendency is for smoke to spread out and to be dissipated, but if the volume is great it may be identified for hundreds of miles, even when the cause of it is unknown....These phenomena, observed from time immemorial, have been known by various names—in this country as dark days, dry fogs, Indian summers, and colored rains."

During the severe fire year of 1987, valleys in northern California and southern Oregon were "smoked in" for weeks, causing anomalous temperature depressions of up to 20°C (Robok 1988). He reported more than 400 people per day were treated for respiratory problems. Tomato plants in Happy Camp died. In 1988, fires burned for four months in Yellowstone National Park. Severe local air pollution problems existed. Wildland firefighters made about 12 000 medical visits because of respiratory problems during the four months (Ward et al. 1989b). Fire-related phenomena are being investigated. For example, one large-scale research fire in the Province of Ontario, Canada, produced a smoke cloud that had numerous discharges of lightning, over 50 mm of precipitation, and washout of a significant fraction of the suspended smoke. Smoke-related phenomena of historical time are now beginning to be understood scientifically.

FIRE PROCESSES

Within the perimeter of an advancing fire, different combustion processes of flaming, smoldering, and glowing compete for available fuel and are markedly different phenomena that contribute, in part, to the diversity of combustion products. The fuel characteristics (including arrangement, size distribution, moisture, and chemical composition) affect the dura-

tion of the flaming, smoldering, and glowing combustion phases.

Flaming and smoldering are distinct combustion processes that not only appear different, but involve different chemical reactions. Flaming combustion dominates during start-up, with the fine fuels and surface materials supplying the volatile fuel required for the rapid oxidation reactions to be sustained in flaming. The heat from the flame structure and the diffusion and turbulent mixing of oxygen at the surface of the solid fuel contribute to the heat required to sustain the pyrolysis processes. Early in the flaming phase, the volatile hydrocarbons are vaporized from the fuels. Later the cellulosic and lignin-containing cellular materials decompose through pyrolysis. These processes produce the fuel gases that sustain the visible flaming processes.

Once carbon begins to build up on the solid fuel surfaces, the pyrolytic reactions no longer produce sufficient fuel gases to maintain the flame envelope. For combustion to continue, oxygen must diffuse to the surface of the fuel. Diffusion of oxygen and the availability of oxygen at the fuel surface is enhanced through turbulence in the combustion zone and through premixing by introducing the oxygen at ground level. This allows oxidation to take place at the solid fuel surface and provides for heat evolution and heat feedback to accelerate the pyrolytic reactions and volatilization of the fuel gases from the solid fuel. The process ultimately leads to the production of charcoal, where the only combustion occurring is of the glowing type—a surface reaction of oxygen with carbon.

The Sundance Fire was a typical high-intensity wildfire with all of the combustion processes described above taking place simultaneously and on a large scale (Anderson 1968). Flame lengths undoubtedly exceeded 50 m. Fire-induced winds would have exceeded 40 m/s coupled with strong updrafts estimated to be as high as 40 m/s. The resultant winds would have produced phenomenal turbulence within the combustion zone and within the lower troposphere. Large pieces of partially consumed fuel particles were carried long distances and deposited ahead of the main fire front. Major pockets of unburned hydrocarbon gases undoubtedly exploded periodically above the main fire front. No research has yet examined emissions from such a violent fire. However, inferences of emissions can be made from data now available.

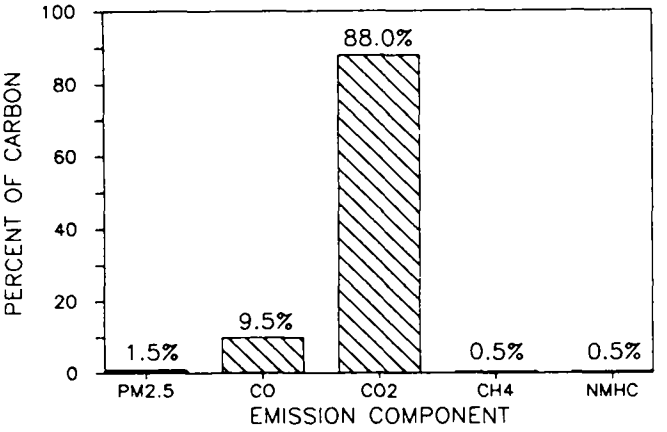

Fig. 1. The average percentage of total carbon released by biomass burning in the United States in the form of CO, CO_2, and hydrocarbons. PM2.5 is particulate matter less than 2.5 μm diameter.

SMOKE PRODUCTION

The smoldering combustion phase produces high emissions of particulate matter and CO. Fires of low intensity (those in which the flaming combustion phase is barely sustained) produce high emissions of particulate matter. The formation of particulate matter results primarily from two processes: (1) the agglomeration of condensed hydrocarbon and tar materials, and (2) mechanical processes that entrain fragments of vegetation and ash.

Release of carbon

When biomass fuels are burned, carbon is released in the form of CO_2, CO, CH_4, hydrocarbons, particulate matter, and other substances in decreasing abun-

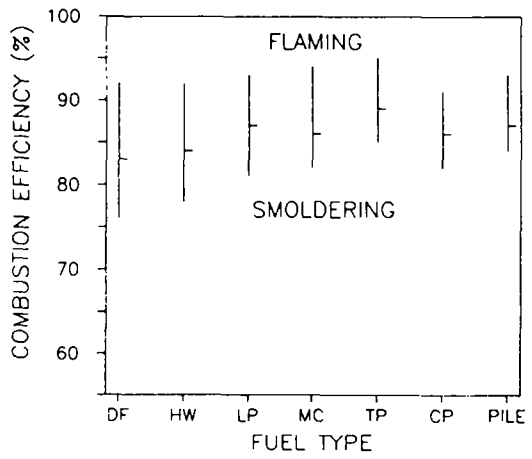

Fig. 2. Combustion efficiency for seven fuel types for flaming, smoldering, and weighted average. (DF-Douglas-fir, HW-Hardwood, LP-Ponderosa pine and lodgepole pine [long-needled conifers], MC-Mixed conifer, TP-Tractor piled, CP-Crane piles, and Pile-Combined TP and CP.).

dance (Fig. 1). A carbon mass-balance procedure is frequently used to characterize the fuel consumed in producing the emissions measured (Radke et al. 1990; Ward and Hardy 1984; Ward et al. 1979). The sum of CO_2 and CO accounts for more than 95% of the carbon released during the combustion of biomass. Combustion efficiency is calculated from the measured concentrations of carbon-containing gases and particles above background released from the combustion of biomass fuels. The combustion efficiency is never 100% for biomass burned in the open environment and generally ranges from 50 to 95%. Generally, the combustion efficiency is lowest for the smoldering combustion phase and highest for those fires with good ventilation and vigorous flame action. Combustion efficiency is illustrated in Fig. 2 for seven fuel types tested in the Western United States. In this paper, combustion efficiency is used as the independent variable for modeling the rate of release of emissions.

Formation of particles

Forest fires are a complex form of the diffusion flame process where pyrolysis of solid fuels produces fuel gases that interdiffuse with oxygen from the atmosphere. As the interdiffusion of fuel and oxygen develops and intensifies, the flame characteristics and the chemical processes occurring in the flame zone change. It is highly probable that, for the Sundance Fire, a level of fire intensity was above that associated with optimal combustion efficiency. Under these extreme fire intensity conditions, fuel may no longer pass through an active oxidation zone. At times, even in lower intensity fires, pockets of unburned, partially oxidized gaseous fuels escape the combustion zone or undergo delayed ignition. The influence of flame turbulence on combustion efficiency is not fully understood. However, as the intensity of the fire increases and the zone of complete mixing of gaseous fuel and oxygen moves farther from the solid fuel, combustion efficiency is believed to decrease and the abundance of the products of incomplete combustion to increase.

Because of the increased depth and height of the flame zone, heading fires and area fires create an extended reducing environment in which continued pyrolysis and synthesis of hydrocarbon gases and fragmented particles can occur under conditions of reduced oxygen content. (A "heading fire" moves with the wind. An "area fire" may result from the ignition of many point fires within a sizable area, and these point fires joining together forming a large region totally involved in flaming combustion.) In addition, heat is reradiated from the particles to the atmosphere, which can slow down the reactions as the unburned gases and particles are convected away from the active combustion zone. If the temperature in the interior of the flame zone is appropriate (<800°C), rapid formation of particles and accretion of carbonaceous organic particles will occur. Consumption of the particles requires prolonged exposure at high temperatures (>800°C) in a zone with near ambient (21%) concentration of oxygen (Glassman 1977).

Mass-fire experiments performed in Canada during 1988 and 1989 demonstrated the important effect of oxygen deficiency on flame structure and on emissions production (Susott et al. in press). The pulsation phenomenon often observed for large fires is thought to be closely coupled to oxygen deficiency. Oxidation of the particles depends partly on the degree of premixing of pyrolyzed fuel and oxygen that takes place in the zone of active solid fuel pyrolysis. Greater premixing results in production of less particulate matter.

Particle number and volume distribution

The size and content of smoke particles have significant health implications. Small diameter particles (fine particles less than 2.5 μm in diameter) may be drawn deep into the human lung and are defined as the respirable fraction. The respirable fraction contains particles of a diameter that also have a maximum effect on visibility and radiation transfer in the atmosphere. The concentration of smoke particles by diameter classes has been measured using sophisticated instruments aboard aircraft to cover the broad distribution of particle sizes from 0.01 μm to 43 μm (Radke et al. 1990). The results suggest a pronounced number concentration peak at a diameter of 0.15 μm. The volume distribution that, for a first approximation, represents the mass distribution was found to be bimodal with peaks at 0.5 μm and greater than 43 μm (Fig. 3).

Ward and Hardy (1984) measured a large difference in emission factors for particles of the respirable size range (PM2.5) as compared to particles without regard to size (PM). This difference increased proportionally to an increase in the rate of heat release on an area basis (Fig. 4). They noted a slight decrease in emission factors for PM2.5 with an increase in PM emission factors over the range of rates of heat release tested. Radke et al. (1988) noted a similar increase in PM emission factors and concurred that this increase probably results from an increased level of turbulence in the combustion zone.

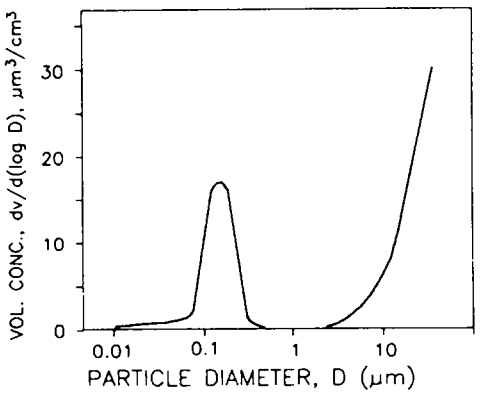

Fig. 3. Volume by particle size fractions measured for prescribed fires of logging slash in the Western United States from an airborne sampling platform (Radke et al. 1990).

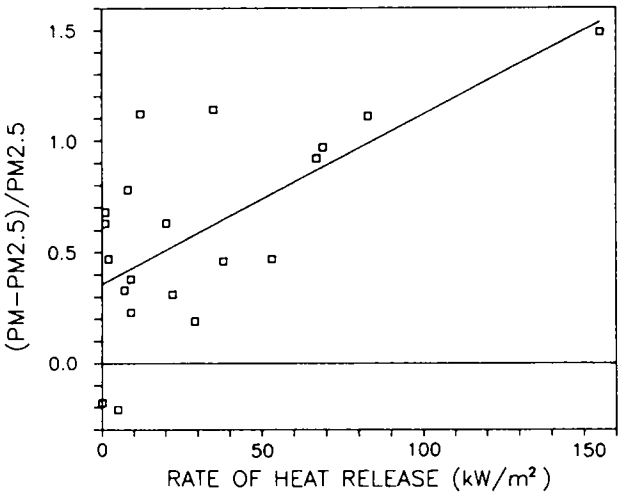

Fig. 4. The ratio of differences between emission factors for total particulate matter and particulate matter less than 2.5 μm as a function of the rate of heat release.

Emission factors for particulate matter

Ward et al. (1988) summarized those emission factor data available for different fuel types by region within the United States. For chaparral fuels in the Southwest, palmetto gallberry of the Southeast, and possibly sagebrush of the Intermountain West, similar PM emission factors of about 15 g/kg can be used. The emission factors for PM for long-needled conifer litter fuels burned with backing and heading fires range from 20-50 g/kg of fuel consumed, respectively. Fires in cured grass generally have lower emission factors of 10 g/kg of fuel consumed. The emission factors are quite similar for broadcast burns of logging slash, regardless of species, ranging from 11-13 g/kg, 12-14 g/kg, and 18-20 g/kg of fuel consumed for PM2.5, PM10, and PM, respectively. Emission factors for piled logging slash with no soil incorporated in the pile are 4, 4, and 6 g/kg of fuel consumed for PM2.5, PM10, and PM, respectively. For piled slash, when the pile contains 35% organic soil mixed with the woody fuel, the emission factors range up to 35 g/kg of fuel consumed.

Although many measurements of the concentration of emissions have been made, ancillary data regarding fuel and fire conditions associated with the production of the measured emissions are often lacking. Airborne sampling of emissions from fires is often poorly supported by ground truth observations or measurements. Generally, investigators recognize the combustion efficiency differences between flaming and smoldering combustion phases. But the composite samples taken using airborne systems have seldom been effective differentiating either combustion phase. For many fuel types, emissions from the smoldering phase overwhelm emissions produced through flaming combustion processes—typical of measurements of smoke from wildfires and during the later stages of prescribed fires.

The emissions sampling system of Ward and Hardy (1984) was used to measure PM and PM2.5 emission factors for several different fuel types in Washington, Oregon (Ward et al. 1989a), and California (Ward and Hardy 1989). The data for PM and PM2.5 are plotted as a function of combustion efficiency in Fig. 5. Regression models indicate a 35% increase in the PM emission factors over the emission factors for PM2.5 for the same levels of % combustion efficiency (CE). For PM and PM2.5, the regression equations are:

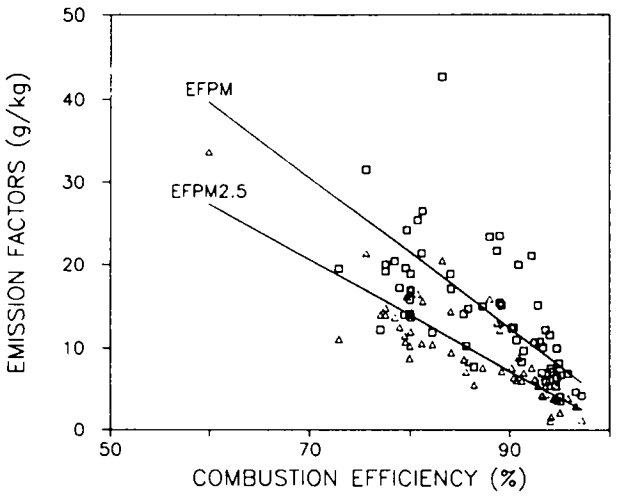

Fig. 5. Emission factors for total particulate matter (PM) and for particles less than 2.5 μm diameter (PM2.5) as functions of combustion efficiency.

$$EFPM = 93.3 - 90.5*CE, \quad R^2 = 0.54; \quad (1)$$

and

$$EFPM2.5 = 67.4 - 66.8*CE, \quad R^2 = 0.74. \quad (2)$$

Standard error of the estimate values for the regression lines are ±3.0 g/kg and ±6.3 g/kg for Equations 1 and 2, respectively. The standard error of the estimate values illustrate the variance that has not been explained due to combustion efficiency. Combustion efficiency is defined in the previous section, "Release of Carbon." As combustion efficiency decreases, the emission factors for PM and PM2.5 increase. The PM and PM2.5 models are used in a later section to compute the source strength for the Sundance Fire.

Hegg et al. (1989) found nearly identical results for a single fire sampled in Canada. Their plot of CO and CO_2 ratios are converted to combustion efficiency and used as the independent variable. The slope of the regression line (EFPM = 108.6-108.0*CE, R^2 = 0.71) is similar to Equation 1. Data were collected during a pilot study in Brazil of one savanna-like (cerrado area) and two tropical deforestation fires (Ward et al. 1990). These fires show high values of combustion efficiency ranging from 92-97% and the emission factors for PM less than 5.0 µm diameter ranged from 4-7 g/kg. Both sets of data superimpose nicely on Fig. 5.

Other factors such as rate of heat release have a pronounced effect on the size and mass of particles produced. Generalized models are needed, based on factors affecting fire spread, fuel consumption, and combustion efficiency for predicting the production of smoke.

The results of Ward and Hardy (1984) demonstrated for a number of fuel types that (1) emissions of particulate matter range over a factor of 10 depending on fire and fuel conditions that affect combustion efficiency; (2) brushy areas produce the most smoke per ton of fuel consumed and have higher rates of production of benzo[a]pyrene than non-brushy areas; (3) fires of higher intensity (long flame lengths) produce proportionately larger particles than are found in low-intensity and smoldering combustion fires; (4) CO is abundantly produced from open fires and, generally, on a mass basis exceeds the production of particles by a factor of 10; (5) hydrocarbon gases are a small part of the total amount of carbon released from the combustion of forest fuels; and (6) emission factors for particles released from fires tend to increase inversely to combustion efficiency (Ward et al. 1989a).

Emissions of trace elements

The trace elements for samples of PM2.5 are shown in Fig. 6 as a percentage of the PM2.5 by combustion phase and weighted for the entire fire. All the samples of the trace elements are from broadcast burns of logging slash from coniferous species. The sodium component is especially high for the flaming phase; nearly 2.75% of the PM2.5 is sodium.

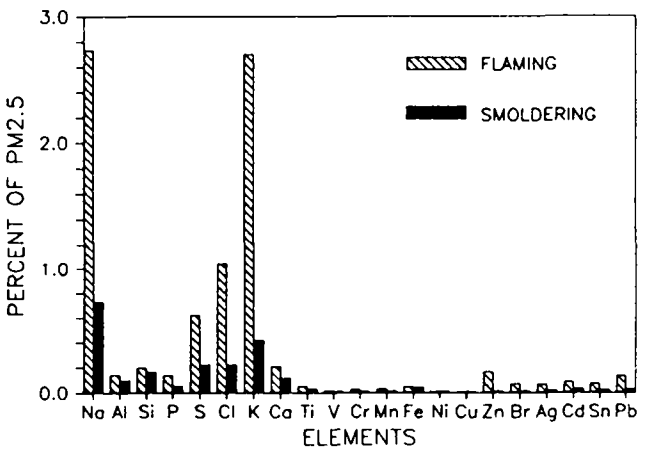

Fig. 6. Percentage composition of particulate matter less than 2.5 µm diameter in smoke from logging slash fires in the Western United States.

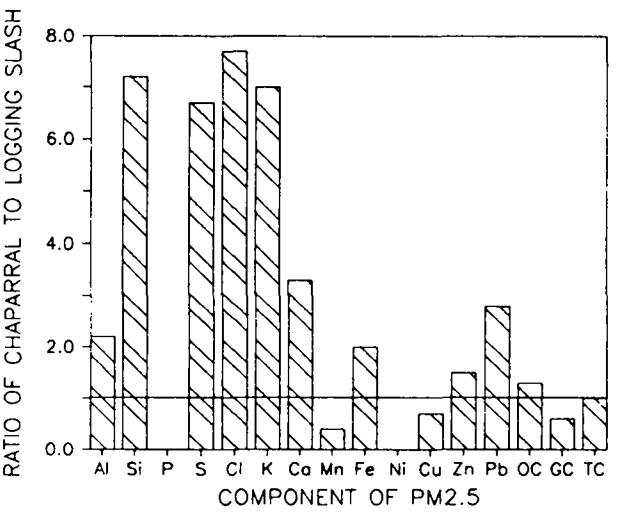

Fig. 7. Ratio of trace element content for smoke from logging slash and chaparral fires in the Western United States.

The sodium, sulfur, chlorine, and potassium contents of PM2.5 are high during the higher temperature flaming phase of the fire. Generally, as the combustion efficiency increases, more of the carbon is consumed, thus increasing the percentage of mass reported as trace elements. Ward and Hardy (1984) found that the sum of sulfur, chlorine, and potassium (S + Cl + K) is correlated with the rate of heat release (r = 0.92). Iron released with the PM2.5 is slightly greater during the latter periods of the smoldering phase than during the flaming phase or first part of the smoldering phase. The large difference in potassium content in the combustion phase leads to accentuating the potassium-to-carbon ratio differences by combustion phase. Potassium was released proportional to the rate of heat release.

Differences in emissions of trace elements were noted as a function of fuel type by Ward and Hardy (1988; 1989). The average values for trace materials produced with the PM2.5 during the flaming phase were generally higher for the chaparral fires of California than for the logging slash broadcast fires of the Washington and Oregon areas (Fig. 7). The production of sulfur, chlorine, and potassium for the chaparral fires was an order of magnitude larger than for the slash fires. Fire intensity was much higher for some of the chaparral test fires than for the logging slash fires. The fire intensity ranged up to a maximum rate of heat release on a square meter basis of nearly 3 MW—or nearly an order of magnitude larger than for the logging slash fires. Emissions of lead from fires in southern California were high relative to fires in the Pacific Northwest. We currently do not have adequate information to separate the effects of the rate of heat release and fuel chemistry in the prediction of the content of particles. It is generally accepted that the trace elements are released in the highest proportion to the carbon contained with the particles for the highest intensity fires. However, the lead content may be higher for the California fires because of a higher deposition rate in the California area from sources outside the forest environment.

Emissions of graphitic and organic carbon

Emissions of graphitic carbon are especially important because of the contribution to the absorption of light. Because the absorption by the smoke emissions is due primarily to graphitic carbon, the specific absorption coefficient correlates well with the graphitic carbon content of the aerosol (Patterson et al. 1986). Emission factors for graphitic carbon were found to range from 0.46-1.18 g/kg of fuel consumed for logging slash of the Pacific Northwest. In tests of pine needle (slash pine) fires in a controlled environment combustion laboratory, emission factors were measured as high as 5.40 g/kg of fuel consumed. The results suggest an inverse correlation between specific absorption and emission factors. This is in agreement with the inverse correlation of the rate of heat release with the percentage graphitic carbon content reported by Ward and Hardy (1984). Generally, emission factors for PM2.5 have been found to be lower for higher intensity fires.

Organic carbon content of particulate matter is especially important because of the types of organic compounds associated with the particles. The polynuclear organic material is contained as a fraction of the organic carbon content of the particles, and contains the important class of compounds known as polynuclear aromatic hydrocarbons—some of which are known to have carcinogenic properties. The carbon fraction of the organic content of particulate matter ranges between 30 and 60%. Benzo[a]pyrene is the most studied of the compounds contained in this fraction. Emission ratios were found to range from 2-274 μg/g of particulate matter for heading and backing fires, respectively (McMahon and Tsoukalas 1978). Measured ratios of benzo[a]pyrene to particulate matter were reported in the range of 0.4-222 μg/g of particulate matter for fires in coniferous species logging slash in the Western United States (Ward 1989). The highest values occur for the smoldering combustion phase and lowest for the flaming combustion phase for the highest intensity fires.

Emissions of CO and other trace gases

CO is the second most abundant carbon-containing gas produced during the combustion of biomass (Fig. 1). Combustion efficiency is highly correlated with the ratio of the production of CO relative to CO_2 (Fig. 8). Ward (1989) found particulate matter concentration to be correlated with CO concentration (r = 0.89). Reinhardt (1989) found the concentration of formaldehyde to be correlated with the concentration of CO (r = 0.93). Generally, emission factors for CO on a mass basis are 10 times greater than for the fine particle fraction. Emission factors for CO range from 60 g/kg to over 300 g/kg of fuel consumed.

During several days of sampling haze layers in the Amazon region of Brazil using airborne and real time sampling techniques, Andreae et al. (1988) found a molar ratio of elevated CO to elevated CO_2 of 0.085. This ratio was used for calculating emissions of other materials. Their CO to CO_2 ratio gives a calculated

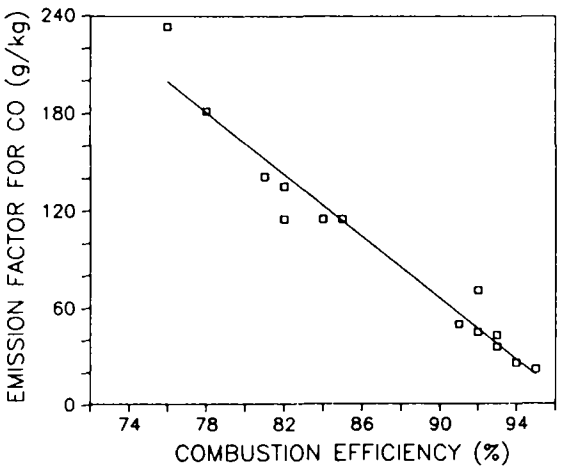

Fig. 8. Functional relation for CO and combustion efficiency.

emission factor for CO of 87 g/kg of fuel consumed. Also working in Brazil, Crutzen et al. (1985) measured concentrations of CO, CO_2, and selected hydrocarbons using mostly grab-sampling, ground-based sampling techniques. The calculated range of emission factors for CO for these measurements ranged from 167-209 g/kg. This is generally higher than the fire-weighted average emission factors for logging slash fires in the Western United States of 171 ±42 g/kg. Hegg et al. (1989) reported emission factors for CO of 91 ±21 g/kg of fuel consumed. Their measurements were for several fuel and fire types on the West Coast of the United States and in the Province of Ontario, Canada. These differences may be a result of either vegetation or moisture content differences, or both.

The large differences between Hegg et al. (1989), Ward et al. (1989a), Andreae et al. (1988), and Crutzen et al. (1985) cannot be resolved through combustion efficiency arguments and differences in fuel and fire complexes. Airborne sampling of emissions from biomass fires often involves measurements of emissions that are a few µL/L above the background concentration. The background concentration of CO_2 can vary dependent on time of day, solar insolation, mixing in the lower boundary layer, and the location of the experiment relative to urban sources. In addition, airborne samples may include a disproportionate quantity of emissions from the flaming combustion phase because the plume is generally much more buoyant during the times of maximum rates of heat release. On the other hand, measurements of emissions from fires taken a few meters above the flames may not allow enough time for adequate quenching.

Table 1. Mean values of emission factors for compound x divided by the associated emission factor for CO as presented by Hegg et al. (1989).

Compound x	EFx/EFCO
O_3	0.060 +/- 0.05
NH_3	0.014 +/- 0.008
CH_4	0.031 +/- 0.003
C_3H_6	0.006 +/- 0.001
C_2H_6	0.005 +/- 0.002
C_3H_8	0.003 +/- 0.001
C_2H_2	0.003 +/- 0.001
N_2H_4	0.002 +/- 0.002
N_2O	0.004 +/- 0.001
NO_x	0.070 +/- 0.040

Despite questions concerning the representativeness of the measurements of CO emission factors, the airborne measurements are the most extensive set of data available today, and the supporting measurements of trace gases expressed as a ratio to CO are equally valuable. The emission factor ratios of Hegg et al. (1989) are listed in Table 1 and will be used in the projections for the Sundance Fire, United States' contribution to the global budget of trace gases, and revised projections for the global emissions.

Of critical importance are the correlations of the concentration of other combustion products with the concentration of CO. Ward et al. (1989a) cross-correlated emissions data from near full-scale experimental fires for six fuel types and found highly significant positive correlation coefficients between CO and the following emissions: PM (0.80), PM2.5 (0.84), CO_2 (0.63), CH_4 (0.88), and nonmethane hydrocarbons (0.79). This suggests that the production of CH_4 and possibly other low-molecular weight hydrocarbons can be scaled to the production of CO as listed in Table 1. In addition, Ward et al. (1989a) found combustion efficiency cross correlation coefficients to be highly significant with emission factors for the compounds: EFPM (-0.73), EFPM2.5 (-0.83), EFCO (-0.97), $EFCH_4$ (-0.75), EFNMHC (-0.62), and $EFCO_2$. The regression models as a function of combustion efficiency (CE) are:

$$EFCH_4 = 42.7 - 43.2*(CE), \quad R^2 = 0.77; \tag{3}$$

$$EFCO = 961 - 984*(CE), \quad R^2 = 0.95; \tag{4}$$

and

$$EFCO_2 = 1833*(CE). \tag{5}$$

The algorithm for computing $EFCO_2$ values is derived from the definition of combustion efficiency and the chemical composition of biomass ($C_6H_9O_4$). The ratio $EFCH_4/EFCO$, calculated for the regression equations 3 and 4, ranges from 0.046 at 75% combustion efficiency to 0.065 at 95% combustion efficiency. This compares with the ratio of Hegg et al. (1989) in Table 1 of 0.031 and the range of values presented by Cofer et al. (1989) of 0.040-0.068 for combustion efficiencies ranging from 87-91%.

The same argument is much less convincing for the nitrogen-based species listed in Table 1. In general, NO_x varies proportionally to the nitrogen content of the fuel (Clements and McMahon 1980). The ozone concentration may only be remotely related to either NO_x or the concentration of reactive hydrocarbons and may be more closely coupled with the level of insolation receipt (Evans et al. 1977). Andreae et al. (1988) extensively studied haze layers over the Amazon region of Brazil and found ozone production contributed significantly to the regional ozone budget during the dry season when most of the burning occurs.

THE SUNDANCE FIRE: A CASE EXAMPLE

The Sundance Fire is used as an example to calculate source strength functions for the various emissions, not because it was an extremely large fire (reaching a maximum size of 22 626 ha), but because the fire growth and fuels contributing to the main fire front and the subsequent smoldering zone were well-quantified. In addition, the Sundance Fire is typical of fires that have a high rate of growth during one diurnal period. As with most wildfires, there is little opportunity to quantify the fuels prior to the fire. Therefore, the fuel consumption must be reconstructed by knowing the forest type; sampling fuels from adjacent unburned areas of similar vegetation, composition, and disturbance history; and from interviews with fire management personnel with a familiarity of the fire and the site. The Sundance Fire was well-documented by a team of scientists from the Intermountain Fire Sciences Laboratory in Missoula, Montana (Anderson 1968).

The fire burned during a time of extreme drought coupled with low humidity, high temperature, and high wind speeds. The net result was a fire that moved rapidly, covering 25.7 km between 1400 and 2300 h on September 1, 1967, with a convection column that reached 10.3 km into the atmosphere. The fire burned through mixed conifer forests interspersed with logged areas. It crowned through the young and overmature stands equally and with little regard for stand density. The crown fuel consumption ranged from 0.46-1.17 kg/m^2 with the brush consumption averaging 0.61 kg/m^2. The ground litter and duff consumption ranged from 0.22-4.48 kg/m^2.

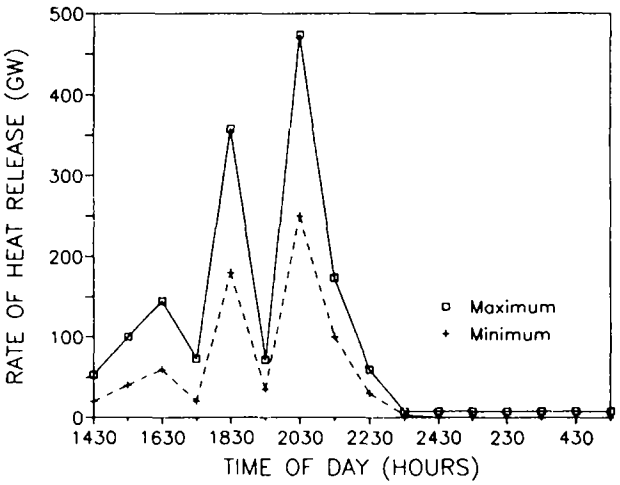

Fig. 9. Maximum and minimum rates of heat release for the main fire front of the Sundance Fire, September 1-2, 1967 (Anderson 1968).

Total maximum and minimum rates of heat release for the advancing fire front were estimated by Anderson (1968) for each hourly increment of time (Fig. 9) dependent on the available fuel as well as intelligence reports of the location of the fire perimeter. The maximum rate of heat release of 500 GW occurred at about 2000 h with estimated wind speeds of 20 m/s from the southwest. This period coincides with the time of maximum expected rate of release of emissions.

This paper uses the estimates of maximum rates of heat release for the main fire front to calculate the fuel consumption for three fire environments: (1) for the main fire front, (2) for the area of secondary flaming (not linked with the main fire front), and (3) for the area immediately following the flaming combustion where fuel was consumed by the smoldering combustion process. The available data are used in the following way to compute the rate of fuel consumption:

(1) The assumption was made (Anderson 1968) that all of the crown, brush, and 20% of the ground fuel (litter and decomposed plant parts) were consumed through the flaming combustion process (except for a period from 1700 to 1800 h discussed below). Only a portion of the heat release from this fuel contributed to the fire front. These estimates and the proportional breakdown between the fuel con-

sumption that occurred in the active fire front and the secondary flaming zones are presented in Table 2. Anderson (1968) provided maximum and minimum fuel loadings for the ground and crown fuel components. Average values were used in the calculations: 0.82, 0.61, and 2.35 kg/m^2 for the crown, brush, and ground fuel consumption, respectively.

(2) Values of percentage consumption for each of the three classes of fuels were used in developing a weighted heat release for each hour of the fire (Table 2). This hourly value was divided into the total maximum heat release for the flame front (Fig. 9) to calculate the fuel consumption for the active flame front.

(3) The balance of the fuels consumed in the zones of secondary flaming combustion was used to calculate a ratio of fuels consumed between the secondary and active fire fronts (Table 3). This ratio was multiplied by the fuel consumption per m^2 for the active fire front to compute the total fuel consumption on a per-m^2 basis in the zone of secondary flaming combustion.

(4) The smoldering combustion process was assumed to have consumed 80% of the ground fuel except for one period from 1700 to 1800 h, when 30% of the ground fuel contributed to the heat entering the convection column from the main fire front. Table 3 shows the ratio of smoldering to flaming by hourly increments. These ratios were multiplied by the total flaming fuel consumption to calculate the total mass of fuel consumed (on a per m^2 basis) through smoldering combustion.

(5) Smoldering combustion was assumed to reach a maximum rate of consumption immediately following the flame front passage and to die exponentially over a 12-h period (Ward and Hardy 1984). The smoldering fuel consumption was computed using the following equation:

$$W_s = (1 - FP)\,(2.35\ \text{kg/m}^2)\,(1 - \text{EXP}\,(-T/t)) \qquad (6)$$

where

FP = percentage consumption during flaming phase,

T = time since ignition, hours,

t = decay time to consume 63% of total, 1 h.

As a result, 99.8% of the smoldering combustion fuel consumption occurred in the first 8 h following ignition. Equation 6 uses a longer decay constant than that measured by Ward and Hardy (1984) for the

Table 2. Fuel consumption data for Sundance Fire (Anderson 1968) and the calculation of the weighted heat release based on the fuel consumption by type.

Time	Main fire front fuel consumption			Main fire front fuel consumption			Total primary flaming	Weighted heat release
	Ground	Brush	Crown	Ground	Brush	Crown		
	-(dimensionless)-			-------(kg/m^2)----------				(kJ/g)
1430	0.20	0.75	0.10	0.471	0.454	0.082	1.007	17.73
1530	0.20	0.90	0.40	0.471	0.545	0.327	1.343	17.38
1630	0.10	0.95	0.80	0.235	0.575	0.654	1.464	16.95
1730	0.30	0.85	0.20	0.706	0.515	0.163	1.384	17.64
1830	0.10	0.90	0.95	0.235	0.545	0.776	1.557	16.84
1930	0.06	0.95	0.60	0.141	0.575	0.490	1.207	17.05
2030	0.06	0.60	0.95	0.141	0.363	0.776	1.281	16.61
2130	0.04	0.70	0.80	0.094	0.424	0.654	1.172	16.72
2230	0.06	0.80	0.70	0.141	0.484	0.572	1.198	16.89
2330	0.06	0.60	0.50	0.141	0.363	0.409	0.913	16.95
2430	0.06	0.60	0.50	0.141	0.363	0.409	0.913	16.95
0130	0.06	0.60	0.50	0.141	0.363	0.409	0.913	16.95
0230	0.06	0.60	0.50	0.141	0.363	0.409	0.913	16.95
0330	0.06	0.60	0.50	0.141	0.363	0.409	0.913	16.95
0430	0.06	0.60	0.50	0.141	0.363	0.409	0.913	16.95
0530	0.06	0.60	0.50	0.141	0.363	0.409	0.913	16.95
0630	0.06	0.60	0.50	0.141	0.363	0.409	0.913	16.95
0730	0.06	0.60	0.50	0.141	0.363	0.409	0.913	16.95
0830	0.06	0.60	0.50	0.141	0.363	0.409	0.913	16.95
0930	0.06	0.60	0.50	0.141	0.363	0.409	0.913	16.95
1030	0.06	0.60	0.50	0.141	0.363	0.409	0.913	16.95
1130	0.06	0.60	0.50	0.141	0.363	0.409	0.913	16.95
1230	0.06	0.60	0.50	0.141	0.363	0.409	0.913	16.95
1330	0.06	0.60	0.50	0.141	0.363	0.409	0.913	16.95

Table 3. Fuel consumption by type for the Sundance Fire (Anderson 1968) and the multiplier for calculating fuel consumption for the secondary flaming and smoldering combustion zones.

Time	Secondary flaming fuel consumption				Factor for secondary flaming	Factor for smoldering
	Ground	Brush	Crown	Total		
	-------(kg/m^2)----------				(Dimensionless	
1430	0.000	0.151	0.734	0.886	0.880	0.995
1530	0.000	0.061	0.490	0.550	0.410	0.995
1630	0.235	0.030	0.163	0.429	0.293	0.995
1730	0.000	0.091	0.653	0.744	0.537	0.774
1830	0.235	0.061	0.041	0.337	0.216	0.995
1930	0.330	0.030	0.326	0.686	0.569	0.995
2030	0.330	0.242	0.041	0.613	0.478	0.995
2130	0.377	0.182	0.163	0.721	0.616	0.995
2230	0.330	0.121	0.245	0.695	0.581	0.995
2330	0.330	0.242	0.408	0.980	1.073	0.995
2430	0.330	0.242	0.408	0.980	1.073	0.995
0130	0.330	0.242	0.408	0.980	1.073	0.995
0230	0.330	0.242	0.408	0.980	1.073	0.995
0330	0.330	0.242	0.408	0.980	1.073	0.995
0430	0.330	0.242	0.408	0.980	1.073	0.995
0530	0.330	0.242	0.408	0.980	1.073	0.995
0630	0.330	0.242	0.408	0.980	1.073	0.995
0730	0.330	0.242	0.408	0.980	1.073	0.995
0830	0.330	0.242	0.408	0.980	1.073	0.995
0930	0.330	0.242	0.408	0.980	1.073	0.995
1030	0.330	0.242	0.408	0.980	1.073	0.995
1130	0.330	0.242	0.408	0.980	1.073	0.995
1230	0.330	0.242	0.408	0.980	1.073	0.995
1330	0.330	0.242	0.408	0.980	1.073	0.995

diedown phase of broadcast burns of logging slash. The reasoning is that the fire severity was much greater than normally encountered when using prescribed fire. Generally, as the fuel moisture content declines below about 35%, on an oven-dry weight basis, the ground fuels are consumed independently of the woody fuels and litter (Sandberg and Ottmar 1983). In this case, the forest floor fuel moisture content ranged from 8-20%.

(6) The ratio of smoldering to flaming fuel consumption as distributed using the exponential decay function (Equation 6) is used to generate Table 4.

(7) Hourly incremental fuel consumption for the flame front, secondary flame area, and smoldering, along with the cumulative fuel consumption for the three fuel consumption categories are presented in Table 5. In particular, the maximum rate of fuel consumption occurred between 2000 and 2100 h and reached a rate of 0.28 Tg/h. The total fuel consumption for the Sundance Fire is estimated to be 1.02 Tg. This is about 1% of the total biomass consumed annually within the United States by all wildland biomass fires.

Source strength calculations for the sundance fire

To calculate source strength for a fire, the rate of fuel consumption must be known (Table 5) along with the appropriate emission factors (Fig. 10) for the gases and particles.

For the Sundance Fire, about 50% of the mass of the fuel was consumed through smoldering combustion. This affected the types and quantity of emissions produced as was discussed previously in the section on "Smoke Production." The rate of consumption of fuels involved in smoldering combustion peaks almost immediately following the flaming combustion period, and then dies out at a rate approximating an exponential decay function, with the time constant being dependent on the dryness of the compact fuel layers and the depth of the duff layer (Ward and Hardy 1984).

The combustion efficiency for the Sundance Fire is thought to be similar to that for many broadcast prescribed burns of logging slash. For prescribed burns of logging slash from harvesting of Douglas-fir/western hemlock forests, the combustion efficiency ranges from an average of 77% for smoldering com-

Table 4. Distribution of fuel consumption for the smoldering combustion component. Note that the exponential decay function (text, Equation 6) is used to distribute the consumption for the smoldering combustion phase based on the total fuel consumed through the flaming combustion process.

Time	Smoldering combustion fuel consumption by hourly areas (elapsed time, hours)												Total for hour
	1	2	3	4	5	6	7	8	9	10	<'''>	16	
	(kg/hour)												
1430	13421												13421
1530	4937	19366											24303
1630	1816	7124	26401										35341
1730	668	2621	9712	15188									28189
1830	246	964	3573	5587	61737								72107
1930	90.4	355	1314	2055	22712	15820							42347
2030	33.3	130	484	756	8355	5820	100728						116307
2130	12.2	48.0	178	278	3074	2141	37056	40153					82940
2230	4.5	17.7	65.4	102	1131	788	13632	14772	13407				43919
2330	1.7	6.5	24.1	37.6	416	290	5015	5434	4932	2277			18434
2430	0.6	2.4	8.9	13.8	153	107	1845	1999	1814	838	2277		9059
0130	0.2	0.9	3.3	5.1	56.3	39.2	679	735	668	308	838...>		5610
0230		0.3	1.2	1.9	20.7	14.4	250	271	246	113	308...>		4341
0330			0.4	0.7	7.6	5.3	91.9	100	90.3	41.7	113...>		3874
0430				0.3	2.8	2.0	33.8	36.6	33.2	15.3	41.7		3702
0530					1.0	0.7	12.4	13.5	12.2	5.6	...>	2277	3639
0630						0.3	4.6	5.0	4.5	2.1	...>	838	1338
0730							1.7	1.8	1.7	0.8	...>	308	492
0830								0.7	0.6	0.3	...>	113	180
0930									0.2	0.1	...>	41.7	66.1
1030										0.0	...>	15.3	24.3
1130											...>	5.6	8.9
1230											...>	2.1	3.3
1330											...>	0.8	1.2
1430											...>	0.3	0.4
1530											...>	0.1	0.1
1630												0.0	0.0

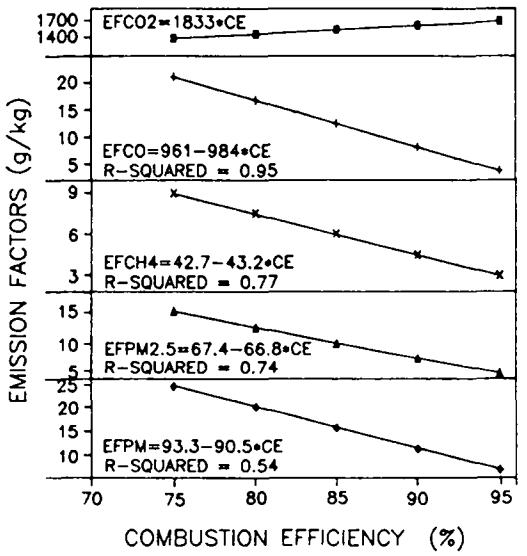

Fig. 10. Emission factors for PM, PM2.5, CH_4, CO, and CO_2 are functions of combustion efficiency. For the Sundance Fire, combustion efficiencies of 90 and 75% were used for the flaming and smoldering combustion phases, respectively.

bustion to about 92% for the flaming phase (Ward et al. 1989a). For airborne samples of smoke from wildfires in Oregon during 1987, Hegg et al. (1989) quantified emission factors for CO_2, CO, and hydrocarbons. Here, combustion efficiencies are calculated from their measurements for the smoke of the Silver Fire in southern Oregon of 89% and for the Myrtle Creek Fire, 88.7%.

Combustion efficiency values of 75% for the smoldering phase and 90% for the flaming phase are used for the Sundance Fire. From Fig. 10 and Equations 1 to 5, the corresponding emission factors for PM, PM2.5, CH_4, CO, and CO_2 for the flaming phase are 11.9, 7.3, 3.8, 75.0, and 1650 g/kg, respectively, and for the smoldering phase are 25.4, 17.3, 10.3, 222.6, and 1375 g/kg, respectively.

Hourly emissions of PM, PM2.5, CH_4, CO, and CO_2 are presented in Table 6. The rate of fuel consumption was cyclic with three major peaks occurring that are correlated with the rate of heat release

Table 5. Hourly fuel consumption for the main fire front, secondary flaming area, and smoldering combustion for the Sundance Fire.

Hour	Primary flame	Secondary flame	Total flaming	Smoldering	Cumulative
	(Gg/h)				(Tg)
1430	11.35	9.99	21.33	13:42	0.035
1530	21.84	8.95	30.78	24.30	0.090
1630	32.46	9.51	41.97	35.34	0.167
1730	15.71	8.44	24.14	28.19	0.219
1830	80.68	17.46	98.14	72.11	0.390
1930	16.03	9.12	25.15	42.35	0.457
2030	108.32	51.80	160.12	116.31	0.734
2130	39.50	24.33	63.83	82.94	0.880
2230	13.48	7.83	21.31	43.92	0.946
2330	1.75	1.87	3.62	18.43	0.968
2430	1.75	1.87	3.62	9.06	0.980
0130	1.75	1.87	3.62	5.61	0.990
0230	1.75	1.87	3.62	4.34	0.998
0330	1.75	1.87	3.62	3.87	1.005
0430	1.75	1.87	3.62	3.70	1.012
0530	1.75	1.87	3.62	3.64	1.020
0630				1.34	1.021
0730				0.49	1.021
0830				0.18	1.022
0930				0.07	1.022
1030				0.02	1.022
1130				0.01	1.022
1230				0.0	1.022
1330					1.022

for the fire (Fig. 9). Flaming and smoldering rates of CO production are illustrated in Fig. 11. Diedown for the smoldering combustion emissions follows the exponential diedown model (Equation 6).

The rate of release over time and total mass of trace gas species can be calculated using the EF_x/EF_{CO} ratios in Table 1. A listing of the rate of release for those gases is provided on an hourly basis in Table 7 and the total trace gas emissions illustrated in Fig. 12. The emissions are scaled to the rate of release of CO which is based on the overall combustion efficiency and mix of smoldering and flaming emissions. The correlation between emission rates for CO and that for CH_4 and nonmethane hydrocarbons is fairly good. For other nitrogen-based compounds, the emissions are scaled more closely to the nitrogen content of the fuel complex (Clements and McMahon 1980). The relation of NO_x to combustion efficiency has not been established.

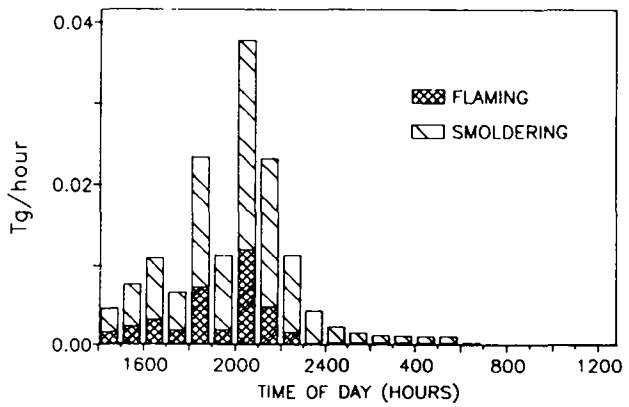

Fig. 11. Hourly rate of production of CO for the Sundance Fire by phase of combustion.

Total emissions

The Sundance Fire was a fast-moving, high-intensity fire that released a tremendous volume of smoke into the atmosphere over a short period. Rates of emission release are presented in Tables 6 and 7. These functions can be integrated to find the total emissions released during the course of the fire. Even though the fire exhibited high rates of heat release and fire growth, the overall magnitude of the emissions produced is less than 0.02% of the emissions

Table 6. Hourly emissions of PM, PM2.5, CH_4, CO, and CO_2 for the flaming phase and the total of flaming plus smoldering for the Sundance Fire, September 1-2, 1967.

Time	PM		PM2.5		CO		CO_2		NO_x	
	FLAM	TOT	FLAM	TOT	FLAM	TOTAL	FLAM	TOTAL	FLAM	TOTAL
1430	0.25	0.59	0.16	0.39	1.60	4.59	35.20	53.64	0.08	0.22
1530	0.37	0.98	0.22	0.65	2.31	7.72	50.78	84.20	0.12	0.37
1630	0.50	1.40	0.31	0.92	3.15	11.01	69.23	117.82	0.16	0.53
1730	0.29	1.00	0.18	0.66	1.81	8.09	39.83	78.58	0.09	0.38
1830	1.16	3.00	0.71	1.96	7.36	23.41	161.90	261.03	0.38	1.12
1930	0.30	1.38	0.18	0.92	1.89	11.31	41.48	99.70	0.10	0.53
2030	1.90	4.85	0.17	3.18	12.01	37.90	264.15	424.04	0.62	1.82
2130	0.76	2.87	0.46	1.90	4.79	23.25	105.30	219.32	0.24	1.10
2230	0.25	1.37	0.16	0.92	1.60	11.38	35.16	95.54	0.08	0.54
2330	0.04	0.51	0.03	0.35	0.27	4.38	5.97	31.32	0.01	0.20
2430	0.04	0.27	0.03	0.18	0.27	2.29	5.97	18.43	0.01	0.11
0130	0.04	0.19	0.03	0.12	0.27	1.52	5.97	13.68	0.01	0.07
0230	0.04	0.15	0.03	0.10	0.27	1.24	5.97	11.94	0.01	0.06
0330	0.04	0.14	0.03	0.09	0.27	1.13	5.97	11.30	0.01	0.05
0430	0.04	0.14	0.03	0.09	0.27	1.10	5.97	11.06	0.01	0.05
0530	0.04	0.14	0.03	0.09	0.27	1.08	5.97	10.98	0.01	0.05
0630	0.00	0.03	0.00	0.02	0.00	0.30	0.00	1.84	0.00	0.01
0730	0.00	0.01	0.00	0.01	0.00	0.11	0.00	0.68	0.00	0.05
0830	0.00	0.01	0.00	0.00	0.00	0.04	0.00	0.25	0.00	0.00
0930	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.09	0.00	0.00
1030	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.03	0.00	0.00
1130	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
1230	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1330										
Totals (Tg)	0.006	0.019	0.004	0.012	0.038	0.151	0.844	1.545	0.002	0.007

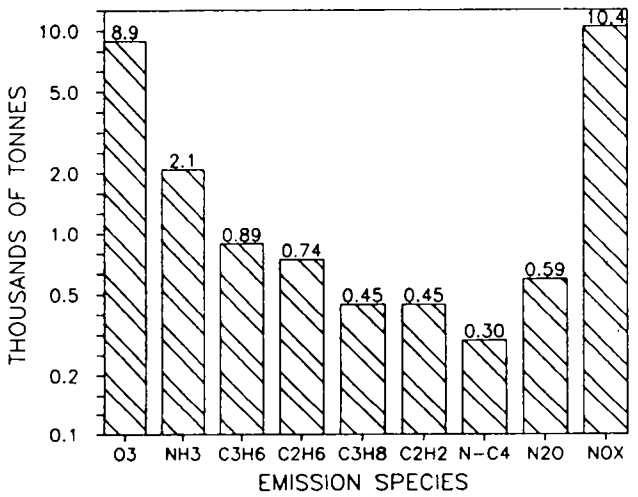

Fig. 12. Total trace gases released from the Sundance Fire.

released globally on an annual basis. Even in the United States, the relative emissions released by one large fire, as the Sundance Fire, are less than 1% of the total released from burning of wildland biomass fires annually.

The total emissions released from the Sundance Fire are thought to be a good model for conifer forest types where a significant ground fuel component exists. For the Sundance Fire, about 50% of the fuel consumption occurred through smoldering combustion. For savanna fires and possibly even tropical deforestation fires, the smoldering component is thought to be much lower. In these cases, higher levels of combustion efficiency would need to be used. This would tend to reduce the emissions of PM, PM2.5, and CO relative to the quantity of biomass consumed. Other sulfur and nitrogen compounds are not correlated through combustion efficiency mechanisms but are more closely coupled to the abundance of sulfur and nitrogen in the fuel complex.

APPLICATION OF EMISSIONS DATA

One application of the emission factors reviewed in this paper is for global estimates of emissions production. In this section, we compare the estimate of emissions for the Sundance Fire with those of

Table 7. Release of trace gases scaled to the release of CO using ratios of Hegg et al. (1989) presented in Table 1.

Time	O_3	NH_3	CH_4	C_3H_6	C_2H_6	C_3H_8	C_2H_2	N-C_4	N_2O	NO_x
	(Gg/h)									
1430	0.275	0.064	0.142	0.028	0.023	0.014	0.014	0.009	0.018	0.321
1530	0.463	0.108	0.239	0.046	0.039	0.023	0.023	0.015	0.031	0.540
1630	0.661	0.154	0.341	0.066	0.055	0.033	0.033	0.022	0.044	0.771
1730	0.485	0.113	0.251	0.049	0.040	0.024	0.024	0.016	0.032	0.566
1830	1.405	0.328	0.726	0.141	0.117	0.070	0.070	0.047	0.094	1.638
1930	0.679	0.158	0.351	0.068	0.057	0.034	0.034	0.023	0.045	0.792
2030	2.274	0.531	1.175	0.227	0.190	0.114	0.114	0.076	0.152	2.653
2130	1.395	0.326	0.721	0.140	0.116	0.070	0.070	0.047	0.093	1.628
2230	0.682	0.159	0.353	0.068	0.057	0.034	0.034	0.023	0.046	0.796
2330	0.262	0.061	0.136	0.026	0.022	0.013	0.013	0.009	0.018	0.306
2430	0.137	0.032	0.071	0.014	0.011	0.007	0.007	0.005	0.009	0.160
0130	0.091	0.021	0.047	0.009	0.008	0.005	0.005	0.003	0.006	0.106
0230	0.074	0.017	0.038	0.007	0.006	0.004	0.004	0.002	0.005	0.087
0330	0.068	0.016	0.035	0.007	0.006	0.003	0.003	0.002	0.004	0.080
0430	0.066	0.015	0.034	0.007	0.006	0.003	0.003	0.002	0.004	0.077
0530	0.065	0.015	0.034	0.007	0.005	0.003	0.003	0.002	0.003	0.076
0630	0.018	0.004	0.009	0.002	0.002	0.001	0.001	0.001	0.001	0.021
0730	0.007	0.002	0.003	0.001	0.001	0.000	0.000	0.000	0.000	0.008
0830	0.002	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.003
0930	0.001	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.001
1030	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1130	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1230	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1330										
TOTALS	9.11	2.126	4.71	0.911	0.759	0.456	0.456	0.304	0.607	10.63

other historical wildfires in the United States. Major fire episodes have occurred in Siberia (Shostakovitch 1925), for example, that produced at least 10^3 times more smoke than the Sundance Fire. Brown and Davis (1973) provide the area burned, lives lost, mechanism of ignition, weather, and general fuels descriptions for several of the larger wildfire episodes in the United States over the past 200 y including the Great Idaho Fire, the Tillamook Fire, the Yacoult Fire, and the Air Force Bomb Range Fire in eastern North Carolina (Wade and Ward 1973). Most of these fires exhibited behavior associated with high intensity, "blowup" fires that probably exhibited major periods of heavy smoke production from smoldering combustion processes.

Assuming that the ratios of flaming to smoldering and the fuel consumption are similar to the Sundance Fire, other major fires are examined based on a comparison of the area burned (Table 8). The ratio of the historical fire area to the Sundance Fire is used as a multiplier for computing the total emissions from the fires listed in Table 8. The procedure used to compute the emissions from the Sundance Fire accounts for the combustion efficiency differences between flaming and smoldering combustion of the fuels.

The emission factors to be used for the analysis of these fires are developed based on a combustion efficiency relationship. In addition, results discussed for prescribed fires are considered in estimating emission factors for wildfires. The larger data base used for developing the combustion efficiency relation can be applied in developing particulate matter and CO emission factors for wildfires. As discussed, some of the emissions are directly correlated with emissions of CO, CH_4, or particulate matter. So, by estimating the source strength of one of the primary combustion products, other emissions source strengths can be estimated.

Now we discuss the application of the combustion efficiency relations presented in this paper as it can be applied to understanding the mixture of emissions released from fires on a global scale. Seiler and Crutzen (1980) estimated global biomass consumption from all major sources and the upper limit of their estimate of 3.3 Pg of biomass carbon consumption is used in Fig. 13 to base the release of other

Table 8. Listing of major fires over the past 200 y in the United States (Brown and Davis 1973) and the estimated emissions of PM, CO, and CH_4. Other emissions can be scaled from the emissions of CO according to the ratios provided by Hegg et al. (1989) listed in Table 2. The area of the Sundance Fire was 22 635 ha.

Fire	Location	Fire area/ Sundance (dimensionless)	Total emissions PM	CO	CH_4
			----(Tg)-----		
Miramichi and and Maine (1825)	New Brunswick and Maine	53.65	1.02	8.15	0.39
Peshtigo and Michigan (1871)	Wisconsin and Michigan	67.60	1.29	10.27	0.49
Far West, Yacoult (1902)	Washington and Oregon	17.88+	0.34	2.72	0.13
Adirondack (1903)	New York	11.39	0.22	1.73	0.08
Great Idaho (1910)	Idaho and Montana	53.65	1.02	8.15	0.39
Tillamook (1933)	Oregon	5.56	0.11	0.84	0.04
Alaska (1957)	Alaska	89.42	1.70	13.58	0.65
(1969)		75.12	1.43	11.41	0.54
Air Force Bomb Range (1971)	North Carolina	0.52-	0.01	0.08	0.01
United States (1988)	Total	89.42-	1.70	13.58	0.65

carbon containing combustion products. We have applied Equations 1 and 3 through 5 in distributing the carbon released among the major emissions released when the biomass fuels are burned in the open environment. If we assume a globally-weighted combustion efficiency of 90%, then 2.97, 0.213, 0.009, 0.023, and 0.008 Pg of carbon is calculated as being released in the form of CO_2, CO, CH_4, particulate matter, and nonmethane hydrocarbons (NMHC), respectively. From Fig. 13, changes in the average combustion efficiency affect the overall mixture of combustion products released to the atmosphere. For example, if the global combustion efficiency for burning of biomass is found to be 95%, then the carbon released as CO_2 would increase by 5%, and that released in the form of other products of incomplete combustion would be decreased by a corresponding amount.

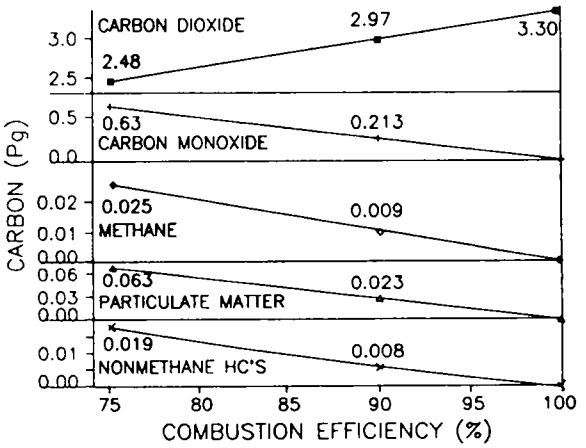

Fig. 13. Global emissions of carbon in the form of CO_2, CO, CH_4, particulate matter, and nonmethane hydrocarbons based on combustion efficiency and the upper limit estimate by Seiler and Crutzen (1980) of the release of 3.3 Pg/y of carbon from burning of biomass fuels.

Other products of combustion can be scaled to one of the primary products of combustion (Hegg et al. 1989, Table 1.). One additional example is provided in Fig. 13 where emission factors for NMHC (C_2-C_6 compounds) are well correlated with emission factors for CH_4 (EFNMHC = 0.760 + 0.616(EFCH$_4$), R^2 = 0.69).

We have demonstrated the application of algorithms for predicting the mix of combustion products from various combustion sources of different biomass fuels globally. The application of the algorithms for fuel types outside of the United States has not been extensively validated. The tests completed and literature values (Crutzen et al. 1985; Andreae et al. 1988) suggest that the mix of carbon-containing emissions released from different biomass fuel types in other regions (for example, Brazil) fits the algorithms developed from extensive field tests of emissions produced from prescribed fires in the Western United States (Ward et al. 1989). It is expected that weighted combustion efficiencies for broad classifications of biomass and fire types can be used with the algorithms presented here to improve the overall estimates of the release of emissions from biomass fires globally.

SUMMARY

Flaming and smoldering combustion processes affect the production of emissions. CO and CO_2 combined account for 90-95% of the carbon released during biomass burning. Combustion efficiency ranges from 50-80% for smoldering combustion and from 80-95% for flaming combustion. Many of the compounds released during biomass burning are correlated with combustion efficiency and can be scaled to the release of CO.

The size distribution for particles produced from biomass burning is bimodal, with particle-mass peaks occurring near 0.5 μm and greater than 43 μm. The abundance of the larger sized particles close to the source are released in relation to the intensity of the fire (rate of heat release per unit area). The mass of particulate matter between 1μm and 10 μm makes up less than 10% of the total mass.

A major wildfire in North America, the Sundance Fire, is used as a model to scale the emissions from several historical fires in North America. The Sundance Fire consumed approximately 1.02 Tg of fuel divided almost equally between flaming and smoldering. Approximately 0.0189 Tg of PM, 0.151 Tg of CO, and 1.54 Tg of CO_2 were released from the 22 635-ha wildfire. Ratios of CO to other trace gases were used to estimate the release of NO_x, NH_3, and N_2O, of 0.0106, 0.0021, and 0.0006 Tg, respectively. It is recognized, however, that the release of nitrogen and sulfur compounds may be more closely coupled to the nitrogen and sulfur content of the biomass.

Global-scale emissions released from the combustion of biomass fuels are difficult to estimate based on a few measurements in the United States. The representativeness of fires in the United States and areas of savanna and tropical deforestation are questioned because of potential differences in fuel chemistry and combustion efficiency. In addition, the combustion efficiency may be much higher for fires of the tropical areas than previously reported. Global biomass consumption inventories should include data on the characteristics of the biomass fuel consumed by the fires for different biomes, the ratio of fuel consumption by flaming and smoldering combustion processes, and the general chemistry of the strata of fuel consumed. These data will facilitate improved estimates of the release of emissions into the atmosphere from both wildland fires and other fires for agricultural purposes using models similar to those presented in this paper and that are presently being developed.

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